

# **NASA Soil Moisture Data Products and Their Incorporation in DREAM**

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## **Executive Summary**

NASA provides soil moisture data products that include observations from the Advanced Microwave Scanning Radiometer on the Earth Observing System Aqua satellite, field measurements from the Soil Moisture Experiment campaigns, and model predictions from the Land Information System and the Goddard Earth Observing System Data Assimilation System. Incorporation of the NASA soil moisture products in the Dust Regional Atmospheric Model is possible through use of the satellite observations of soil moisture to set initial conditions for the dust simulations. An additional comparison of satellite soil moisture observations with mesoscale atmospheric dynamics modeling is recommended. Such a comparison would validate the use of NASA soil moisture data in applications and support acceptance of satellite soil moisture data assimilation in weather and climate modeling.

## 1.0 Introduction

Although soil moisture can be defined as the water content in the upper several meters of ground available for vegetation growth, soil moisture has other far-reaching effects on atmospheric dynamics, land surface hydrology, and civil engineering. Soil moisture is especially important in the atmospheric and hydrologic models used to predict weather and climate. Despite the many applications of soil moisture data, observations of soil moisture are often sparse. *In situ* field measurements provide data only in a local area. Airborne measurements conducted during suborbital campaigns provide broader coverage, but those data are available for only limited time periods. Recurrent, global measurements of soil moisture are made solely by satellite remote sensing, but even those measurements are difficult to make. Global measurements also have many limitations, the main being that the satellite retrievals represent only a shallow, near-surface layer of soil and do not provide critical information about soil moisture in deeper zones. However, interest is increasing in assimilation of satellite measurements into land surface models to better predict vertical profiles as well as spatial and temporal patterns of soil moisture (Reichle et al., 2004).

Surface wetness has been identified as one of the 24 key physical measurements carried out by the Earth Observing System (EOS) program (King, 1999). NASA data products that provide observations and predictions of soil moisture are described in the following sections. Recommendations on incorporation of NASA soil moisture data in the Dust Regional Atmospheric Model (DREAM) are discussed in the last section of this document.

## 2.0 Observations

### 2.1 Satellite Measurements

The Advanced Microwave Scanning Radiometer - EOS (AMSR-E) is a multi-frequency, dual polarization, conically scanning, passive microwave radiometer onboard NASA's EOS Aqua satellite. From Aqua's sun-synchronous, 705-km orbit, AMSR-E scans across a 1450-km swath and provides soil moisture measurements with near-global coverage in two days or less (Njoku et al., 2003). In doing so, AMSR-E continues the heritage of several sensors:

- Scanning Multichannel Microwave Radiometer (SMMR), which operated on the Nimbus-7 satellite from 1978 until 1987,
- Special Sensor Microwave/Imager (SSM/I) series of instruments, which have been deployed on the Defense Meteorological Satellite Program (DMSP) spacecraft since 1987 (currently F13, F14, F15, and F16), and
- Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI) onboard the TRMM satellite, which was launched in 1997.

AMSR-E also improves upon the past microwave radiometers; it doubles spatial resolution of SMMR and SSM/I and combines into one sensor all the spectral channels that SMMR and SSM/I individually possessed. [Table 1](#) lists the spectral and spatial characteristics of the AMSR-E instrument. Noteworthy are differences in shape and size between instantaneous fields of view for various spectral bands.

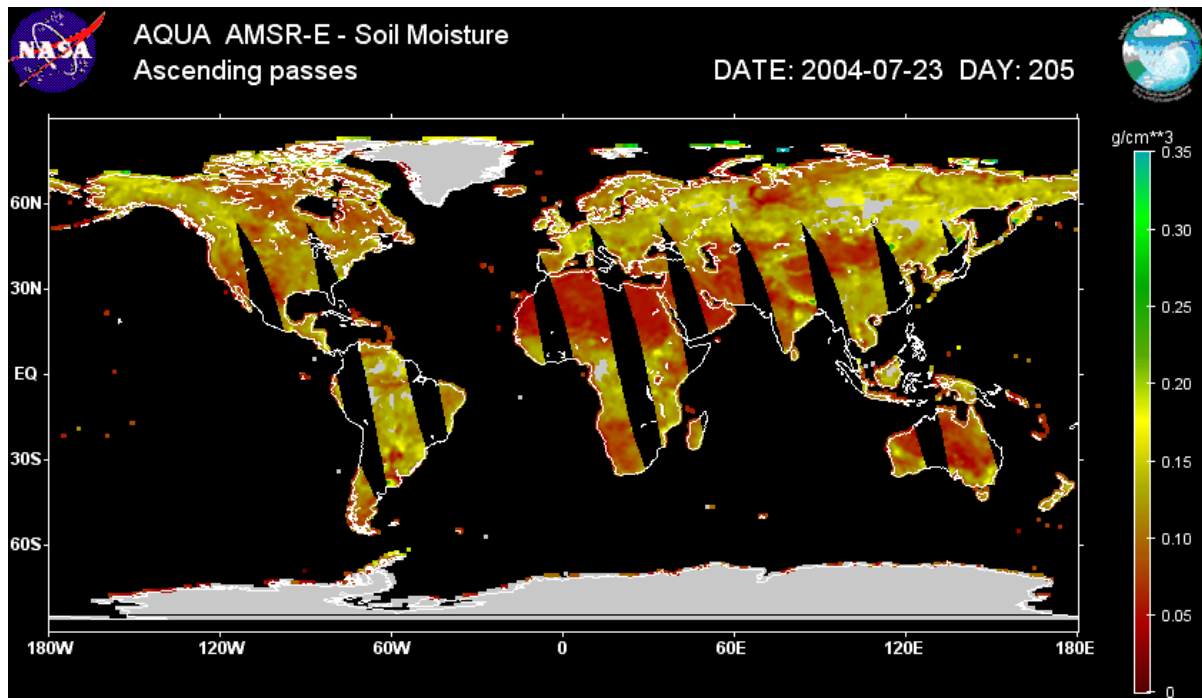
**Table 1.** AMSR-E instrument characteristics.

<b>Band center frequency [GHz]</b>	<b>Instantaneous Field of View (IFOV) [km]</b>
6.925	75 × 43
10.65	51 × 29
18.7	27 × 16
23.8	32 × 18
36.5	14.4 × 8.2
89.0	6.5 × 3.7
89.0	5.9 × 3.5

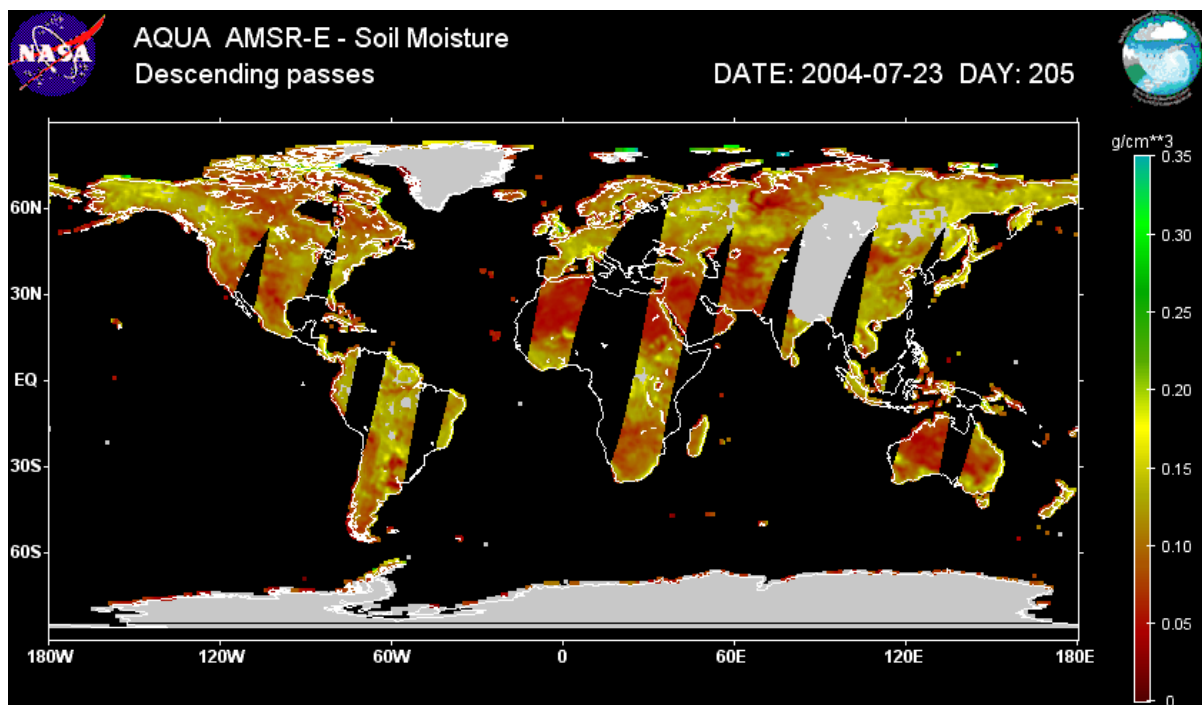
Microwave observations are sensitive to soil moisture through the effects of water content on the dielectric constant and hence the emissivity of the soil. Vegetation and surface roughness reduce this sensitivity, and vegetation and roughness effects become more pronounced as the microwave frequency increases. Furthermore, at lower frequencies, microwave emission originates from deeper soil layers. With the lowest frequency of 6.9 GHz, soil moisture measurements by the AMSR-E instrument are limited to a very shallow surface layer and areas with predominantly bare soil. Still, it is an improvement over the instruments currently deployed on operational weather satellites: SSM/I bands have the lowest frequency of 19.35 GHz. However, there is a concern that measurements at 6.9 GHz are seriously affected by Radio-Frequency Interference (RFI) in many areas of the globe (Li et al., 2004). Future missions, such as the Hydrosphere State Mission (Hydros) (<http://hydros.gsfc.nasa.gov/>), will use a 1.4-GHz band that is less susceptible to effects of vegetation and RFI.

The AMSR-E Level 1A data are generated in Japan at the Earth Observation Center of the National Space Development Agency of Japan, currently the Earth Observation Research and Application Center of the Japan Aerospace Exploration Agency. The Level 1A data contain sensor counts and coefficients needed to compute antenna temperatures and, subsequently, surface brightness temperatures at Level 1B. The Level 1A data are sent to the Physical Oceanography Distributed Active Archive Center (PO.DAAC) located at the Jet Propulsion Laboratory in Pasadena, California. From there the data are transmitted to the U.S. AMSR-E Science Information Processing System (SIPS). The SIPS has two components, one located at the Remote Sensing Systems (RSS) facility in Santa Rosa, California, and the other at the Global Hydrology and Climate Center (GHCC) in Huntsville, Alabama. At the RSS SIPS, Level 2A brightness temperatures are generated by reconstructing the AMSR-E antenna gain patterns at each channel to five footprints, corresponding to the footprint sizes of the 6.9, 10.7, 18.7, 36.5, and 89 GHz observations. The sampling intervals are approximately 10 km for the four low resolutions and 5 km for the highest resolutions. The Level 2A data contain as a subset the Level 1B data. The Level 2A data are sent to the GHCC SIPS for higher-level processing.

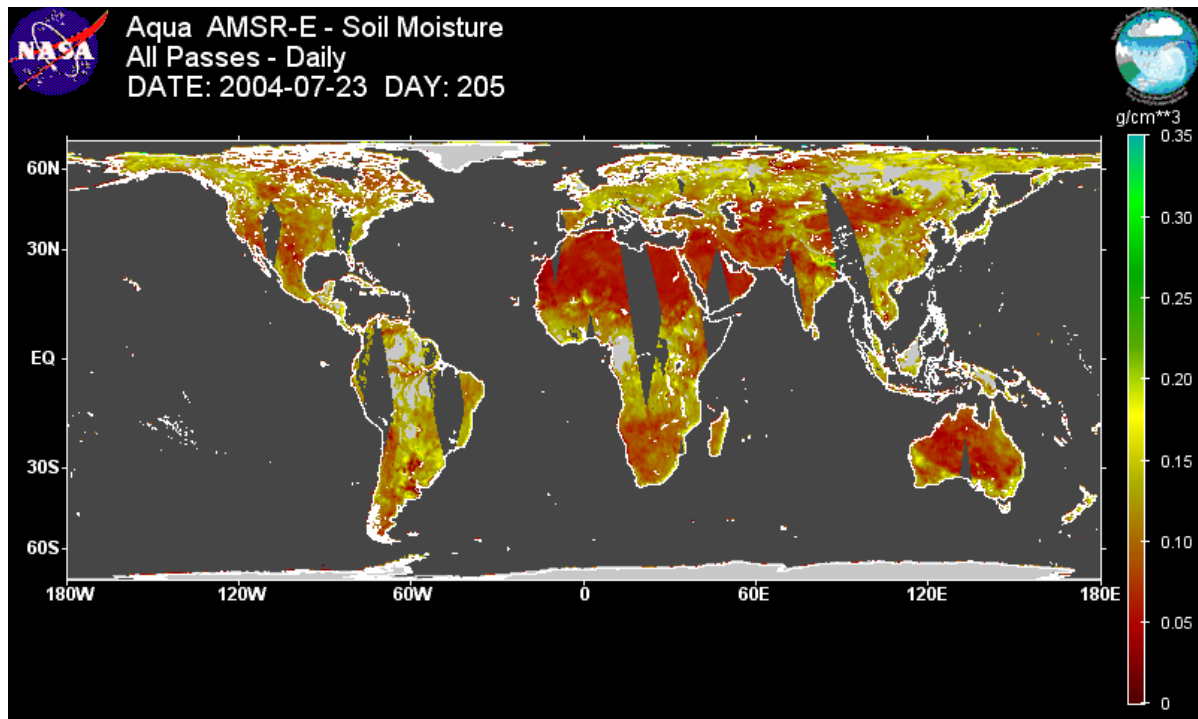
The AMSR-E data products are provided by SIPS in both a pixel-by-pixel, orbital swath projection and in a global space and time averaged (e.g., daily, weekly, or monthly composite) Earth-oriented coordinate grid. The AMSR-E soil moisture data products, AE\_Land (Level 2B) and AE\_Land3 (Level 3), are resampled to a global cylindrical Equal-Area Scalable Earth Grid (EASE-Grid) with 25-km spacing, although spatial resolution of the products is approximately 60 km. Level 2B datasets are separated into subsets acquired during ascending (daytime – [Figure 1](#)) and descending (nighttime – [Figure 2](#)) half-orbits, while the Level 3 datasets include daily global coverage ([Figure 3](#)). The data products are subsequently transferred to the National Snow and Ice Data Center (NSIDC) DAAC in Boulder, Colorado, for archiving and distribution (<http://nsidc.org/data/amsre/>).



**Figure 1.** Daily mosaic of AMSR-E soil moisture measurements during satellite ascending passes.



**Figure 2.** Daily mosaic of AMSR-E soil moisture measurements during satellite descending passes.

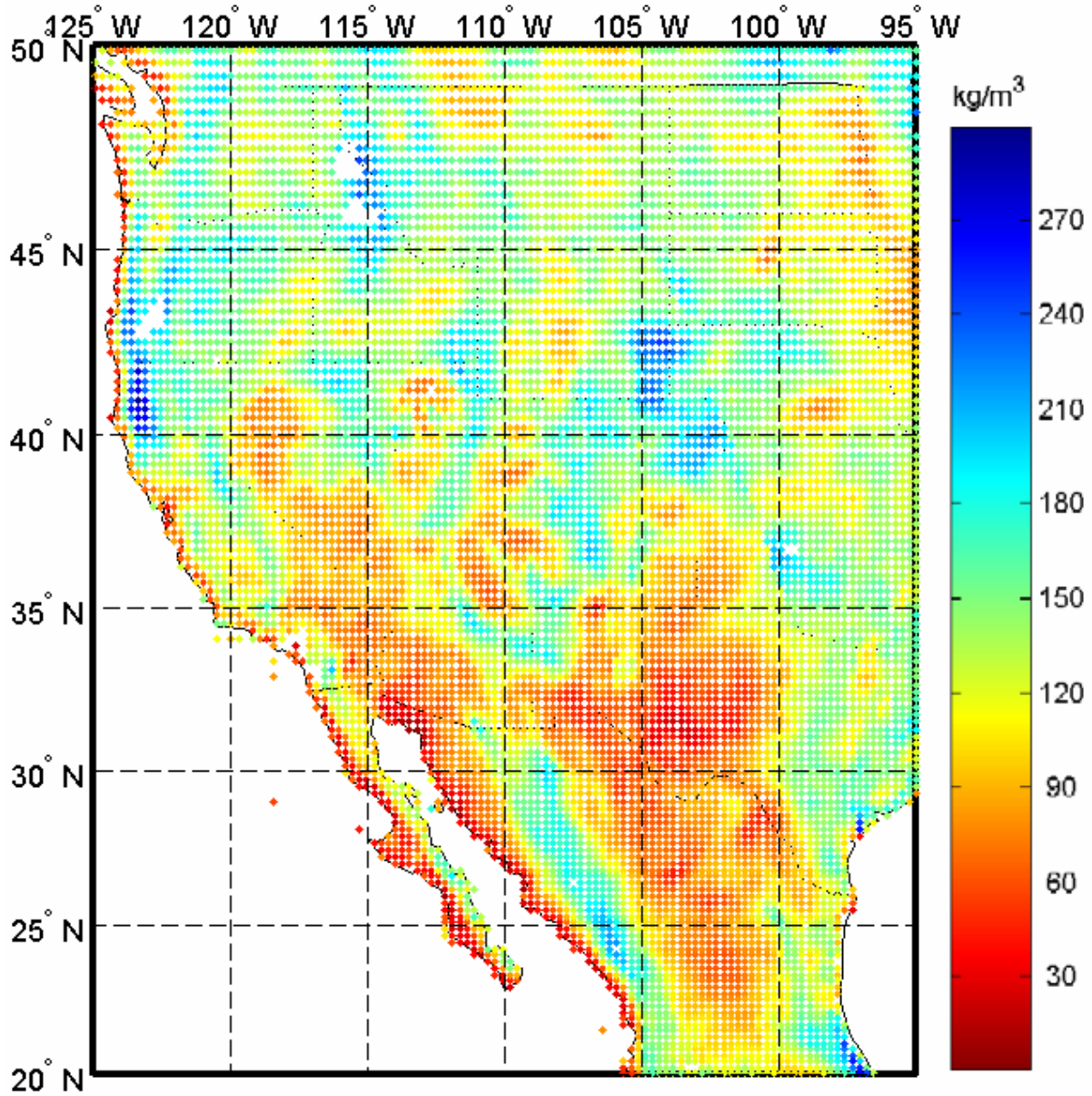


**Figure 3.** Level 3 dataset of AMSR-E soil moisture measurements.

In addition to distributing standard data products, NSIDC hosts a 7-day, rolling archive of preliminary AMSR-E data for those who need data that is closer to near-real-time (NRT) than the final, standard AMSR-E datasets can produce. The NRT archive is updated up to several times per day and usually provides access to datasets acquired on the previous (or even the same) day. Figure 4 shows an example of a soil moisture map created with Level 2B data points retrieved from the NRT archive. Since a single swath of the AMSR-E instrument does not cover the entire area, measurements from multiple passes of the Aqua satellite were combined to create this map on May 3, 2005. The map includes measurements acquired mainly on May 1 and 2, but a small number of the data points originated as early as April 25. The figure illustrates not only the advantages of satellite soil moisture measurements but also the limitations of retrievals in areas that are mountainous, densely vegetated, near coasts, or covered with snow.

The EOS Aqua spacecraft has a direct broadcast X-band downlink that allows AMSR-E data to be received in real time by ground stations having the proper reception hardware and being located in a direct line of sight of the satellite. Since April 2005, the International MODIS/AIRS Processing Package (IMAPP) software has been capable of processing the AMSR-E direct broadcast data to produce calibrated and geolocated AMSR-E Level 1B / Level 2A products. While the AMSR-E processing software was developed by the RSS, it is distributed as part of IMAPP by the University of Wisconsin – Madison (<http://cimss.ssec.wisc.edu/~gumley/IMAPP/IMAPP.html>). Software for further processing of AMSR-E data into Level 2 rain products is available as well. NASA requires developers of algorithms for generation of science products to provide their software code to a DAAC. Such code is subsequently archived and available upon special request from the DAAC (such as the NSIDC). Therefore, generation of AMSR-E soil moisture products from direct broadcast data seems feasible, but it also appears to be less practical and more expensive than downloading the NRT products.





**Figure 4.** Mosaic of NRT AMSR-E soil moisture data for the western United States on May 3, 2005.

## 2.2 Ground Measurements

Soil Moisture Experiments in 2002 (SMEX02), 2003 (SMEX03), and 2004 (SMEX04) were campaigns of airborne and field measurements. Soil moisture data were collected both remotely and *in situ* at the following locations:

- SMEX02: Iowa; June 24 - July 15, 2002
- SMEX03: Oklahoma, Georgia, Alabama; June 23 - July 18, 2003
- SMEX03: Brazil; September 1-10, 2003

- NAME-SMEX04: (North American Monsoon Experiment) Mexico and Arizona; July 15 - August 15, 2004

The SMEX02-SMEX04 datasets have been instrumental in the validation of AMSR-E measurements, but unrestricted access is currently granted only to the SMEX02 datasets:

- SMEX02 Soil Climate Analysis Network (SCAN) Station 2031, Ames, Iowa

This dataset provides data from various sensors on SCAN station number 2031, located near Ames, Iowa. The data include hourly and daily recordings of precipitation, air temperature, solar radiation, wind speed, relative humidity, soil moisture, and soil temperature. The station houses numerous sensors that automatically record data. Sensors include global precipitation sensor, thermistor, thin film capacitance-type sensor, anemometer, pyranometer, pressure sensor, and a frequency-shift dielectric measuring device. Units of measurement vary, depending on the type of sensor. Data are uploaded by meteor burst telemetry to the Natural Resources Conservation Service (NRCS) Data Processing Center in Portland, Oregon. The NRCS has been operating this SCAN station since September 23, 2001, but this dataset covers only the time period of interest to the SMEX02 campaign, June 1 to August 31, 2002. Data are available in two text files: hourly data and daily data.

- SMEX02 Iowa Regional Ground Soil Moisture Data

The parameters for this dataset include gravimetric and volumetric soil moisture, bulk density, and soil temperature. This study was conducted during June and July 2002 in the area around Ames, Iowa. Data were collected in crop fields using a variety of methods and sensors: manual soil samples for gravimetric and bulk density data, infrared pyrometers for soil moisture, and hydra probes for soil moisture and temperature. Data are provided in ASCII text files.

- SMEX02 Soil Moisture and Temperature Profiles, Walnut Creek, Iowa

This dataset contains measurements of soil moisture, soil temperature, and rainfall. Soil moisture and temperature were measured at various depths: 2, 5, 10, 15, 20, and 30 cm. Data were collected in four fields, each containing two measurement sites called "pit A" and "pit B." The study was conducted in the Walnut Creek watershed in south-central Iowa during June and July 2002. Water content reflectometers measured soil moisture. Soil temperature probes and averaging thermocouple probes measured soil temperature. A tipping bucket rain gauge measured rainfall. Data are provided in ASCII text files and a Microsoft Excel<sup>®</sup> file.

- SMEX02 Sliced Core Soil Moisture Data, Walnut Creek Watershed, Iowa

This dataset includes sliced soil core moisture data collected during June and July 2002 in the Walnut Creek watershed in south-central Iowa. The study parameters include gravimetric soil moisture and bulk soil density. Data were collected manually at two corn and two soybean sites. Data are provided as ASCII text files and Microsoft Excel files.

- SMEX02 Watershed Soil Moisture Data, Walnut Creek, Iowa

The parameters in this dataset include gravimetric and volumetric soil moisture, bulk density, soil temperature, soil conductivity, and soil salinity. This study was conducted during June and July 2002 in the area of the Walnut Creek watershed in south-central Iowa. Data was collected in crop fields, using a variety of methods and sensors: manual soil samples for gravimetric and bulk density data, infrared pyrometers for soil moisture, and hydra probes for soil moisture, temperature, and salinity. Data are provided in ASCII text files.

The NSIDC DAAC ([http://nsidc.org/data/amsr\\_validation/soil\\_moisture/](http://nsidc.org/data/amsr_validation/soil_moisture/)) distributes the SMEX02 datasets.

### 3.0 Predictions

The Land Information System (LIS) is a high-performance land surface modeling and data assimilation system, based on Land Data Assimilation Systems developed at Goddard Space Flight Center (GSFC) (Peters-Lidard et al., 2004). LIS calculations include one of three different land surface models:

- CLM, the Community Land Model of National Center for Atmospheric Research,
- NOAH, the community NOAH\* land surface model, and
- VIC, the Variable Infiltration Capacity model.

Predictions of soil moisture for various soil layers are generated as output of any of these models. The modeling can be done at different spatial resolutions, down to 1 km, although requirements for computational resources increase significantly at high resolutions. A key extension to the LIS infrastructure is the capability to perform data assimilations, which are techniques to merge observed data fields with model predictions to improve the subsequent predictions. However, soil moisture assimilation capabilities are not yet implemented in the available LIS software.

Research on assimilation of global satellite observations and soil moisture measurements is also conducted at the GSFC's Global Modeling and Assimilation Office (GMAO). In contrast to the mesoscale LIS modeling, the GMAO calculations are performed on a global scale at much lower spatial resolution – on the order of 100 km (1 degree latitude/longitude). These calculations are based on two land surface models of the NASA Seasonal-to-Interannual Prediction Project: Catchment and Mosaic. Validation against ground-based measurements from the Global Soil Moisture Data Bank in Eurasia and North America demonstrated that soil moisture fields derived from data assimilation are superior to either satellite data or model data alone (Reichle and Koster, 2005).

In the GMAO's operational Data Assimilation System GEOS-4, top soil layer wetness and root zone soil wetness are produced eight times per day (every three hours) as time-averaged fields on the global grid with cells 1.25 degree longitude by 1 degree latitude each. GEOS-4 assimilates observations from a diverse, heterogeneous observing system of land surface, ocean surface, and atmosphere that includes

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\* NOAH is an acronym created from the names of the following institutions: National Centers for Environmental Prediction, Oregon State University, Air Force, and Hydrologic Research Laboratory of the National Weather Service.

several satellite instruments but that does not include remote sensing measurements of soil moisture (i.e., AMSR-E) (Bloom et al., 2005).

## 4.0 DREAM Recommendations

In Dust Regional Atmospheric Model (DREAM), soil moisture is one of the factors controlling production of dust. Soil moisture data used in the dust calculations are generated internally by a coupled atmosphere/land-surface model incorporated in the DREAM modeling system (Nickovic et al., 2001). The calculations are initialized with atmospheric conditions generated by an external, numerical weather forecasting system based on assimilation of meteorological observations. Subsequently, further numerical forecasts from that external system are used to create periodically (e.g., at 6-hour intervals of the simulated time) lateral boundary conditions imposed on the DREAM simulations. These initial and boundary conditions include atmospheric temperature, humidity, and wind velocity.

Use of the AMSR-E satellite measurements of surface soil moisture as initial conditions for the dust simulations provides the best opportunity for application of NASA soil moisture data in DREAM. Field measurements of soil moisture conducted during the SMEX campaigns are not as useful because they were collected at only a few locations and during a limited time span. NASA Earth science models, such as LIS and GEOS, may provide improved soil moisture data in the future, but their functionality for assimilation of AMSR-E and similar observations must first become operational. Otherwise, direct use of AMSR-E soil moisture products is a better choice. Although without assimilation into land surface models AMSR-E provides only measurements of moisture content in a thin surface layer of soil, this may actually be the layer that is essential for production of dust. Moreover, an initial state of the soil moisture field was shown to have an important effect on outcome of the numerical weather forecasting (Chen et al., 2004).

Nevertheless, characteristics and limitations of the current NASA soil moisture observations and predictions need to be better understood. Today's remote sensing of soil moisture delivers groundbreaking Earth observations on a global scale, but its applicability to mesoscale atmospheric modeling, such as in the DREAM simulations, still needs to be verified and validated. Some comparisons of AMSR-E soil moisture observations with field measurements and land surface model predictions have even indicated disagreements (Sahoo, 2004). Therefore, further validation is needed of NASA soil moisture observations for their application in mesoscale modeling. Currently, the atmospheric modeling in DREAM is based on the North American Mesoscale – Eta model developed and used for operational forecasts by the National Oceanic and Atmospheric Administration. In the near future, this model will be replaced by the Nonhydrostatic Mesoscale Model of the Weather Research and Forecasting modeling system (COMET, 2005). Comparisons of AMSR-E soil moisture measurements with results of the operational models should help build confidence in the satellite data and promote its use in applications of national priority.

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